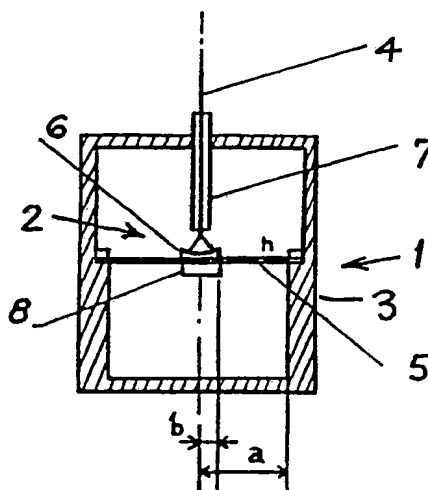




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(21) International Application Number: PCT/GB90/00133 (22) International Filing Date: 30 January 1990 (30.01.90) (30) Priority data: 8902034.1 31 January 1989 (31.01.89) GB (71) Applicant (for all designated States except US): KENT SCIENTIFIC AND INDUSTRIAL PROJECTS LIMITED [GB/GB]; Physics Laboratory, The University, Canterbury, Kent CT2 7NR (GB). (72) Inventors; and (75) Inventors/Applicants (for US only) : JACKSON, David, Alfred [GB/GB]; 8 Woodland Way, Canterbury, Kent CT2 7LS (GB). NEWSON, Trevor, Paul [GB/GB]; 56 Grasmere Road, Chestfield, Whitstable, Kent CT5 3NA (GB). GERGES, Awad, Samir [EG/GB]; 4 Saint Michael's Road, Canterbury, Kent CT2 7HG (GB).		(74) Agents: WARREN, Keith, Stanley et al.; Baron & Warren, 18 South End, Kensington, London W8 5BU (GB). (81) Designated States: AT (European patent), AU, BE (European patent), CA, CH (European patent), DE (European patent), DK (European patent), ES (European patent), FI, FR (European patent), GB (European patent), IT (European patent), JP, LU (European patent), NL (European patent), NO, SE (European patent), US. Published <i>With international search report.</i>

(54) Title: OPTICAL DISPLACEMENT SENSOR**(57) Abstract**

An optical displacement sensor, for example a vibration sensor or accelerometer, in which the relative displacement of a resilient sensing element, such as a diaphragm (5), in response to an external stimulus applied to the sensor, is detected by a Fabry-Perot interferometer (2), and in which one of the mirrors (6) of the interferometer is mounted on the sensing element and the other mirror is formed by the adjacent or distal end of an optical fibre (4) via which the interferometer is illuminated or energised. The means mounting the diaphragm, comprises a housing (1) which may be adapted to be coupled to the external stimulus to be sensed, and the optical fibre (4), which is preferably a mono-mode optical fibre, may also be supported by the housing in a capillary tube (7) so that its optical axis corresponds to the optical axis of the mirror. Another embodiment of the invention comprises a back-to-back configuration in which mirror image Fabry-Perot optical cavities are arranged on either side of a resilient diaphragm sensing element.

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-1-

OPTICAL DISPLACEMENT SENSOR

1 The present invention relates to an optical
displacement sensor, for example, a vibration sensor
or accelerometer, and more particularly, to such a
sensor utilising the principles of a Fabry-Perot
5 type interferometer for sensing vibrations or linear
displacements.

Optical sensors based on interferometry are
known for a wide range of measurands. For example, our
prior International specification No. WO83/03010
10 describes optical displacement sensing apparatus
incorporating a confocal Fabry-Perot interferometer in
which one of the confocal mirrors is resiliently
mounted so that the mirrors are relatively movable in
response to an external stimulus applied to the
15 interferometer, and servo means is responsive to the
optical output from the interferometer to adjust an
optical parameter, upon relative displacement of the
mirrors, in a manner to maintain and restore the
optical transmissivity of the interferometer and
20 thereby monitor the displacement. Conveniently, this
interferometer is addressed via a mono-mode optical
fibre and, similarly, the output from the interfero-
meter may be detected via a second optical fibre.

Optical fibre accelerometers have also been
25 proposed in which a mono-mode optical fibre, itself,
forms part of the sensing element. Although these
devices offer very high resolution, their performance
is critically dependant on the opto-mechanical prop-
erties of the fibre.

-2-

1 The present invention consists in an optical
displacement sensor in which the relative displacement
of a resilient sensing element, in response to an
external stimulus applied to the sensor, is detected
5 by a Fabry-Perot interferometer, and in which one of
the mirrors of the interferometer is mounted on the
sensing element and the other mirror is formed by the
adjacent or distal end of an optical fibre via which
the interferometer is illuminated or energised.

10 The sensor of the invention is particularly
suitable for use as an accelerometer and, as such, is
designed to measure only a single orthogonal component
of acceleration. It shows only a small cross
sensitivity to other components. Perturbations caused
15 by temperature changes may be relatively small and,
with appropriate choice of material, very high temper-
ature operation is possible.

 The sensing element may comprise a diaphragm
weighted so that it remains stationary upon appli-
20 cation of the external stimulus to the sensor. The
means mounting the diaphragm, for example, a housing,
may be adapted to be suitably coupled to the external
stimulus to be sensed, and the optical fibre, which is
preferably a mono-mode optical fibre, may also be
25 supported by the mounting means so that its optical
axis corresponds to the optical axis of the mirror.

 In a preferred embodiment of the invention, the
mirror mounted on the sensing element is a spherical
metal mirror and the distal end of the optical fibre
30 forms both the optical input and output of the

-3-

1 interferometer. A laser light source may be connected
to the proximal end of the optical fibre for supplying
an optical or light signal for illuminating the
interferometer. The output signal transmitted through
5 the optical fibre may be recovered therefrom in any
suitable manner and be detected by a photo-detector
which is connected to supply an electrical signal,
corresponding to the intensity of the optical output,
to signal processing means for providing a measurement
10 of the vibration or displacement sensed by the sensor.
The use of an optical fibre for addressing the sensor
enables the latter to be interrogated remotely.

Conveniently, with the exception of the optical
fibre via which the sensor is addressed, the sensor is
15 of an all-metal construction, including the mirror and
diaphragm or other sensing element. However, for
certain specific applications, other materials, such
as glass, quartz or sapphire may be used for the
diaphragm and/or mirror.

20 The present invention enables the following to
be achieved:-

- 1) a miniature high resolution accelerometer
and vibration sensor;
- 2) an optical cavity formed by an optical
25 fibre end and spherical metal mirror attached to a
sensing diaphragm;
- 3) an optical cavity which can be interro-
gated remotely;
- 4) an all-metal construction (apart from the
30 optical fibre lead) which allows operation at high
temperatures, for example, at least 400°C;
- 5) a diaphragm and mirror which may be made
of non-magnetic materials so that operation in
microwave fields or electrical machines is possible.

1 6) sensitivity which can be tuned by changing
the diaphragm thickness or mass. The range and
resolution of the sensor depends on the properties of
the diaphragm which may be designed appropriately for
5 a given application. The chief environmental perturbation
is that of temperature on the effective spring
constant of the diaphragm. Diaphragm technology is
mature and a range of materials and designs exist
which facilitate the practical implementation of the
10 present invention for a wide range of applications:

7) the mass of the spherical mirror may be
arranged so that it is equally distributed on opposite
sides of the diaphragm to ensure minimum sensitivity
to orthogonal motions - hence, a three-axis configuration
15 is possible;

8) operation as a pressure sensor is possible
by correct choice of the diaphragm thickness.

The sensor according to the invention may be
designed in a back-to-back configuration in which a
20 mirror image of the Fabry-Perot interferometer is
constructed on the opposite side of the resilient
diaphragm or other sensing element.

Such a back-to-back design provides additional
advantages with appropriate optical signal processing.
25 For example, differentially combining the interferometer
outputs doubles the sensitivity and minimises the effects
of source noise. Summing the outputs provides information
regarding the thermal expansion of the assembly enabling the
temperature of the environment to be measured: this may also be used to
30

-5-

1 correct for thermal variation of the spring constant
of the diaphragm, if necessary. Common mode rejection
can be used to improve the accuracy of the sensor.

5 In order that the present invention can be more
readily understood, reference will be made to the
accompanying drawings, in which:-

Figure 1 illustrates an axial section through
one embodiment of the invention;

10 Figure 2 illustrates a block schematic circuit
diagram, including elements for calibrating the sensor
and signal processing for detecting the output of the
sensor;

Figure 3 is a plot illustrating experimental
results;

15 Figure 4 is an oscilloscope picture of inter-
ferometer waveforms; and

Figure 5 illustrates an axial section through a
second embodiment of the invention.

Referring to Figure 1 of the drawings, the
20 sensor 1 comprises a hemispherical Fabry-Perot inter-
ferometer 2 disposed in a cylindrical housing 3 and
illuminated via a mono-mode optical fibre 4 extending
through one end of the housing. Mounted within the
housing is a resilient or elastic diaphragm 5 forming
25 the sensing element and a spherical mirror 6
constituting the outer mirror of the interferometer is
attached to the centre of the diaphragm opposite the
distal end of the optical fibre 4. The latter projects
into the housing through a capillary tube 7 and its
30 distal end, cleaved normally to the axis
of the fibre, forms the inner mirror of the

-6-

1 interferometer. The axis of the fibre 4 is adjusted to
match the optical axis of the spherical mirror and the
cavity length is adjusted to give maximum visibility
of the interference fringes.

5 A suitable mass 8 is secured centrally to the
diaphragm on the opposite side to the mirror 6 so as
to counterbalance the weight of the latter and equally
distribute the weight on either side of the diaphragm
to ensure minimum sensitivity to orthogonal motions.
10 The total weight of the mirror 6 and mass 8 is such
that, when the housing 3 moves in synchronism with and
in response to an external stimulus, the diaphragm 5
remains stationary.

15 Except for the optical fibre 4, all the
components of the sensor 1 illustrated in Figure 1 may
be made from metal to enable the sensor to withstand
high temperature.

The sensing element is constituted by the loaded
elastic diaphragm 5 which effectively has a rigid disc
20 at its centre. The solidity ratio of the diaphragm is
defined as the ratio of the rigid centre and diaphragm
radii (b/a). The spherical mirror 6 is attached
centrally to the rigid centre of the diaphragm. The
static deflection of the centre of the diaphragm is:

$$25 \quad y_s = A_s \frac{F a^2}{16 \pi D} \quad (1)$$

D is called the flexural rigidity of the diaphragm and
A_s is a numerical coefficient which depends on the
solidity ratio [6,7],

$$30 \quad D = \frac{E h^3}{12 (1 - \nu^2)} \quad (2)$$

$$A_s = 4 \left(\frac{c^2 - 1}{4c^2} - \frac{\ln^2 c}{c^2 - 1} \right) \quad (3)$$

-7-

1 where h is the thickness of the diaphragm, E its modulus of elasticity in tension and compression, ν its Poisson's ratio and c is the reciprocal of its solidity ratio ($c=a/b$).

5 For small deflections, the displacement is proportional to the applied axial force (F), and hence to the axial linear acceleration (r). If the mass of the diaphragm is much less than that of the solid central mass (8), the sensing element can be
10 approximated as an equivalent mass spring system. The spring constant is determined from equation (1) as $K=F/Y_0$. The fundamental mode angular frequency of the sensing element is calculated by $\omega_c = \sqrt{K/M}$.

The optical phase change $\Delta\phi$ induced in the
15 hemispherical interferometer (2) by a displacement Y_0 is:

$$\Delta\phi = \frac{4\pi}{\lambda} Y_0 = \frac{r}{\lambda \pi f_0^2} \quad (4)$$

where r is the linear acceleration magnitude to be
20 measured ($r=F/M$), λ is the wavelength of the light illuminating the system and f_0 is the fundamental frequency of the vibrating system. The static resolution (r_{\min}) of the accelerometer is limited by the phase resolution of the interferometer $\Delta\phi_{\min}$ and is
25 a function of the fundamental frequency such that

$$r_{\min} = \lambda \pi f_0^2 \Delta\phi_{\min} \quad (5)$$

Figure 2 illustrates a calibrating and signal processing system used with the sensor. In Figure 2, the housing 3 of the sensor 1 is suitably mechanically

-8-

1 coupled, via its end opposite the optical fibre 4, to
a periodically vibrating test object 9, the acceleration
of whose vibrations is to be measured. The
interferometer 2 is arranged to be illuminated by a
5 laser diode 10, for example, a Mitsubishi L4107, 787
nm, via a directional coupler 11, through which light
is supplied to a calibrating interferometer 12. The
sensor interferometer 2 is addressed via the optical
fibre 4 which also serves as the output channel from
10 the interferometer. The output signal is recovered
from the optical fibre 4 via a directional coupler 13
and is detected by a photodiode detector 14 which
produces an electrical output signal corresponding to
the intensity of the interferometer output signal.
15 This electrical output signal is applied to a feedback
servo 15 for locking the laser diode 10 to maintain
the interferometer 2 at quadrature. It is also fed to
a spectrum analyser 16 which processes the electrical
signal and produces an output corresponding to the
20 acceleration of the periodic vibrations being sensed,
which output, in turn, can be processed to compute the
acceleration.

The calibrating interferometer 12 is also based
upon a hemispherical cavity and is fixed to the top of
25 the sensor housing 3 with its axis parallel to the
direction of vibration. It is addressed via an optical
fibre 17 illuminated by the laser diode 10 and the
output from this calibrating interferometer is
recovered from the optical fibre 17 via a directional
30 coupler 18 and is detected by a photodiode detector 19

-9-

1 which supplies an electrical signal corresponding to
the intensity of the output to an oscilloscope 20.

5 In one experimental test, the vibrating object
or vibrator 9 was driven sinusoidally in the frequency
range 40-900 Hz. The amplitude displacement of the
vibrator (d_{\max}) was set such that the phase change
induced in calibrating interferometer 12 corresponded
to 2π optical radians, (ie, $d_{\max} = \lambda/2$) thus imparting
a calculable acceleration to the diaphragm 5. The
10 spectrum of the intensity output of the interferometer
2 comprises harmonics of the acceleration frequency,
whose amplitudes were measured using the spectrum
analyser 16. By evaluating ratios of harmonic
amplitudes, and using the usual Fourier expansion of a
15 phase modulated signal, the displacement amplitude of
the mirror 6 arising from the acceleration was
determined. This method of signal processing was
expedient and accurate, although more appropriate
techniques exist for use in a practical system. The
20 cross-sensitivity to accelerations orthogonal to the
symmetry axis of the sensor was measured by mounting
the accelerometer with its axis perpendicular to that
of the vibrator.

In the experiment a steel diaphragm 5 with
25 radius of 9.5 mm and thickness of 0.51 mm was used.
The accelerometer 1 was constructed with a curved
mirror 6, radius of curvature ≈ 4 mm. The system was
tested using two different loadings of the diaphragm,
giving masses (8) of 0.91 and 0.59 grams respectively.
30 The first resonance frequency of the diaphragm was 465

-10-

1 and 582 Hz respectively which is in good agreement
with theoretical prediction.

5 The signal to noise ratio was measured using a
vibration amplitude corresponding to one interference
fringe observed at the output of 12, and at a
frequency of 140 Hz. The signal to noise ratio was
found to be 79.2 dBV in a bandwidth of 7.65 Hz,
corresponding to a phase resolution of 4×10^{-5} rad/ $\sqrt{\text{Hz}}$.
10 The noise arises primarily from intensity and
frequency fluctuations of the source and is, hence,
smaller at higher frequencies. The experimentally
determined diaphragm displacements as a function of
frequency were used together with a phase resolution
of 4×10^{-5} rad/ $\sqrt{\text{Hz}}$ to calculate the acceleration
15 resolution, R, of the sensor, and the results are
plotted in Figure 3. It may be seen that the
resolution is better than $5 \mu\text{g}$ ($g = 9.81 \text{ms}^{-2}$). Output
waveforms of the interferometers 2 and 12 are shown in
Figure 4. The cross-sensitivity to orthogonal
20 components of acceleration was measured to be better
than -32.1 dB.

The above described embodiment comprises a
non-electrical accelerometer based upon an all metal
optical cavity which can be interrogated remotely.
25 Acceleration sensitivity exceeds $10^{-6}g$ and it can
operate at temperatures as low as 70K and above 1000K
which cannot be achieved by any form of conventional
accelerometer or contact vibration sensor.

Figure 5 illustrates a back-to-back configur-
30 ation in which mirror image Fabry-Perot optical

-11-

1 cavities 22,23 are arranged on opposite sides of a
resilient diaphragm sensing element 24, whereby common
mode rejection can be utilised to improve the accuracy
of measurements sensed by the sensor 21. Hence, this
5 embodiment comprises a cylindrical housing 25 having
the resilient diaphragm 24 mounted centrally within
the housing. Spherical metal mirrors 26,27 are secured
centrally to opposite sides of the diaphragm and form
the outer mirrors of the respective interferometers.
10 The inner mirrors are formed by the distal ends of
mono-mode optical fibres 28,29 via which each
interferometer is illuminated. Each optical fibre
28,29 is secured in a capillary tube 30,31 extending
through the adjacent end wall of the housing and the
15 axis of its fibre is adjusted to match the optical
axis of its associated spherical mirror. The diaphragm
24 is weighted by the mirrors and, if necessary, by
additional masses in the mirror mountings, so that
when the housing 25 is suitably arranged to detect an
20 external stimulus, the housing moves in synchronism
with the stimulus whilst the diaphragm remains
stationary. Except for the optical fibres 28,29, the
sensor 21 may be an all metal sensor.

25 Whilst particular embodiments have been
described, it will be understood that modifications
can be made without departing from the scope of the
invention. For example, signal processing can be bas-
ed on either homodyne-closed loop; heterodyne-open loop
or white light techniques.

Moreover, other materials other than metals can be used in the construction of the instrument. For example, quartz could be used as the diaphragm material with the mirror cut into the quartz, or ceramics could be used for higher temperatures of operation, i.e. greater than 400°C.

It will be seen that the invention provides a high resolution optical vibration sensor having low weight and also having the ability to carry out a remote operation via a fibre optic link. Moreover, the instrument is not affected by electromagnetic interference (EMI). It also has a low environmental sensitivity to temperature as well as a low environmental sensitivity to source wavelength drift.

-13-

CLAIMS

1. An optical displacement sensor in which the relative displacement of a resilient sensing element, in response to an external stimulus applied to the sensor, is detected by a Fabry-Perot interferometer, and in which one of the mirrors of the interferometer is mounted on the sensing element and the other mirror is formed by the adjacent or distal end of an optical fibre via which the interferometer is illuminated or energised.
 2. An optical displacement sensor as claimed in claim 1, in which the sensing element comprises a diaphragm weighted so that it remains stationary upon application of the external stimulus to the sensor.
 3. An optical displacement sensor as claimed in claim 1 or 2, in which the means mounting the diaphragm, for example a housing, is adapted to be suitably coupled to the external stimulus to be sensed and the optical fibre is also supported by the mounting means so that its optical axis corresponds to the optical axis of the mirror.
 4. An optical displacement sensor as claimed in claim 1, 2 or 3, in which the optical fibre is a mono-mode optical fibre.
 5. An optical displacement sensor as claimed in any preceding claim, in which the mirror mounted on the sensing element is a spherical metal mirror and the distal end of the optical fibre forms both the optical input and output of the interferometer.
 6. An optical displacement sensor as claimed in any preceding claim, in which, with the exception of the optical fibre via which the sensor is addressed, the sensor is of an all-metal construction, including the mirror and diaphragm or other sensing element.
 7. An optical sensor as claimed in any of claims 1 to 5, in which the diaphragm and/or mirror are made of glass, quartz, sapphire or ceramic.
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-14-

8. An optical displacement sensor as claimed in any preceding claim, in which a laser light source is connected to the proximal end of the optical fibre for supplying an optical or light signal for illuminating the interferometer.
9. An optical displacement sensor as claimed in claim 8, in which the output signal transmitted through the optical fibre is recovered therefrom and detected by a photo-detector which is connected to supply an electrical signal, corresponding to the intensity of the optical output, to signal processing means for providing a measurement of the vibration or displacement sensed by the sensor.
10. An optical displacement sensor as claimed in any preceding claim and comprising a back-to-back configuration in which mirror image Fabry-Perot optical cavities are arranged on either side of a resilient diaphragm sensing element.
11. An optical displacement sensor as claimed in any of the preceding claims 1 to 9, comprising a hemispherical Fabry-Perot interferometer disposed in a cylindrical housing and illuminated via a mono-mode optical fibre extending through one end of the housing.
12. An optical displacement sensor as claimed in claim 11, in which a resilient or elastic diaphragm forms the sensing element and a spherical mirror constituting the outer mirror of the interferometer is attached to the centre of the diaphragm opposite the distal end of the optical fibre.
13. An optical displacement sensor as claimed in claim 12, in which the optical fibre projects into the housing through a capillary tube and its distal end forms the inner mirror of the interferometer.
14. An optical displacement sensor as claimed in claim 12 or 13, in which a mass is secured to the diaphragm on the opposite side to the mirror so as to counter balance

-15-

the weight of the latter.

15. An optical displacement sensor as claimed in claim 10, comprising a cylindrical housing having the resilient diaphragm mounted centrally within the housing and spherical mirrors secured centrally to opposite sides of the diaphragm to form the outer mirrors of the respective interferometers.

16. An optical displacement sensor as claimed in claim 15, in which the inner mirrors are formed by the distal ends of mono-mode optical fibres secured in a capillary tube extending through the adjacent end wall of the housing and the axis of each fibre is adjusted to match the optical axis of the associated spherical mirror.

17. An optical displacement sensor as claimed in any preceding claim, including a calibrating interferometer fixed to mounting means for the sensor with its axis parallel to the direction of vibration.

18. An optical displacement sensor as claimed in claim 17, in which the output of the calibrating interferometer is detected by a photodiode detector which supplies an electrical signal corresponding to the intensity of the output to an oscilloscope.

19. An optical displacement sensor substantially as hereinbefore described with reference to Figures 1 to 4 of the accompanying drawings.

20. An optical displacement sensor substantially as hereinbefore described with reference to Figure 5 of the accompanying drawings.

1/3

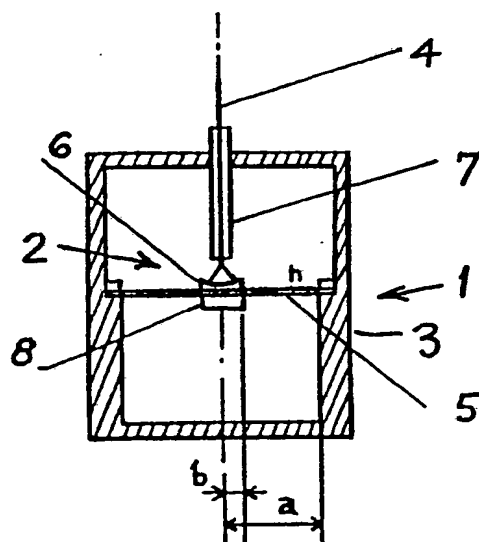


Fig. 1

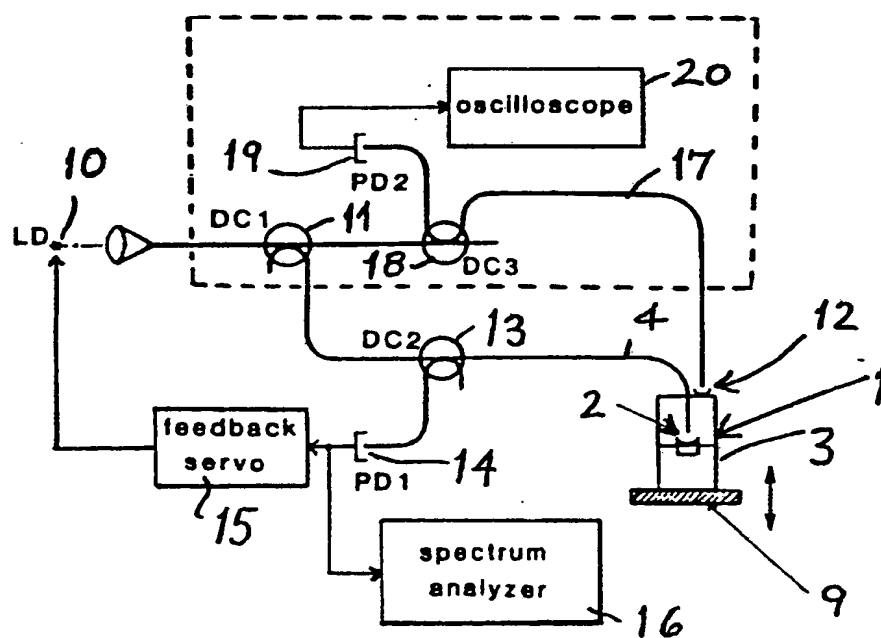


Fig. 2

2/3

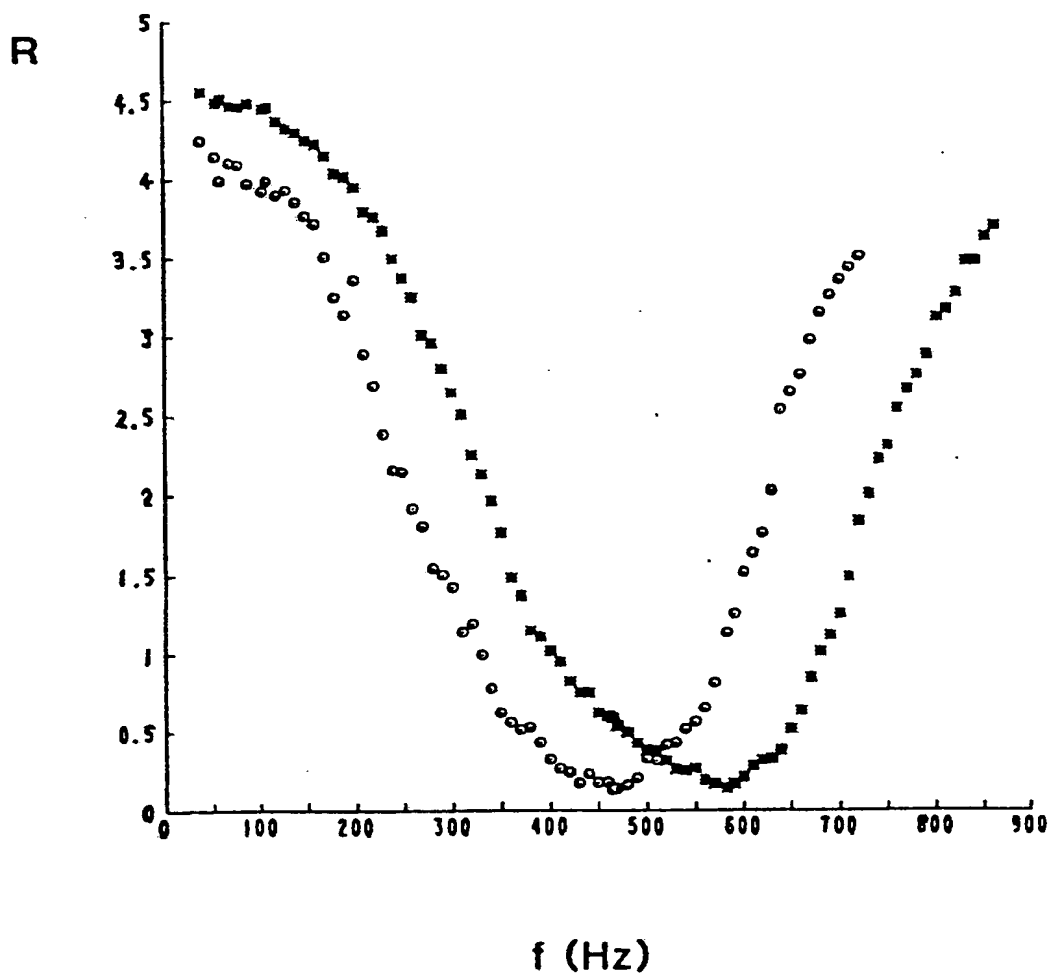


Fig.3

3/3

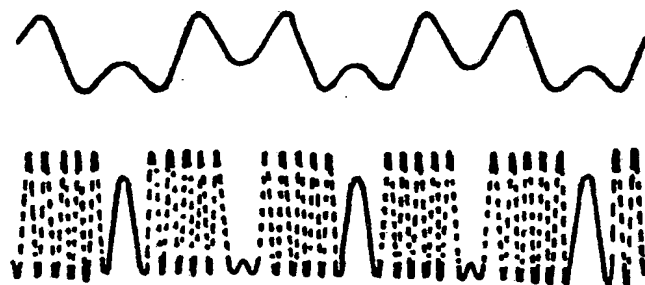


Fig.4

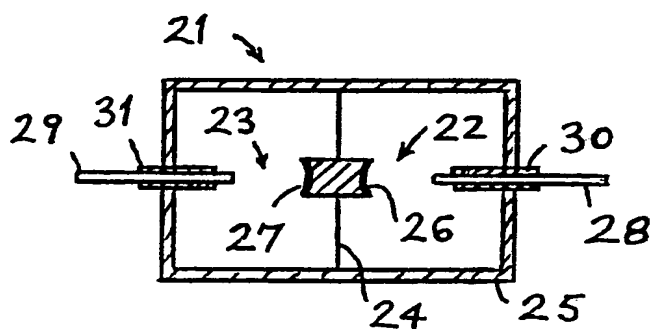


Fig.5

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